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Cover Page Footnote

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Abstract. As well reserved depleted and limited, it is necessary to lower the capital expenditure so that lifting SZ reservoir be more profitable. This article first contextualizes the effort done to increase the hydrocarbon lifting in a mature field. Despite the importance to sustain the production, and massive studies done to quantify the associate risk, no structured methodology proposed to manage the risk in respect to optimize the production expenditure by selection of carbon steel as alternative for corrosion resistance material piping. Hence, this article proposed a framework to support the decision-making process to operate in safely manner. Real case study proposed and evaluated shown 6.72-millimetre metal loss due to SEC and CO_2 corrosion is expected to occur within 5 years' design life. Hence, carbon steel pipe is allowed considering the risk mitigation define are provided and continuously monitored. Results shows the proposed framework increase the confidence level in putting the assessment results into proper decision-making process whilst improving the integrity management system.

Keywords: Carbon Steel, CO_2 Corrosion, Erosion Corrosion, Risk Management, Oil and Gas Production, Sweet Environment

INTRODUCTION

Gas reservoir commonly classified into two (2) zone, namely main zone (MZ) and shallow zone (SZ). Gas drilling at MZ risk considered lower compared to SZ due to SZ consist unconsolidated sandstone and more prone to sand production.(1) Even though downhole well architecture already equipped with sand controlled, small sand size still produces in conjunction with production fluid. Therefore, the main challenge and interest of this study is how top facilities adapt to this condition.

As the sand continue produce, production line become more prone to internal thinning due to corrosive fluid and solid-particle erosion corrosion (SEC). Severity of SEC also increased as reservoir pressure decrease. At low (LP) to very low pressure (VLP) production, in accordance with Bernoulli's effect, fluid velocity expected to increase. As consequence, metal thinning rate increased. Therefore, it is preferable to utilize material that more resistance to corrosion with extra thickness to compensate the metal loss due to SEC.

Unfortunately, as well reserves depleted and limited, utilization of corrosion resistance piping material being challenged to lower the capital expenditure. Projection to shorter design life (less than 5 years) shows low economic benefit in production SZ, if production line to be constructed in corrosion resistance material (CRA). Other important key to be consider is how dynamic the production rate will be as consequence of fluctuate gas price, where there will be possibility of increasing production flowrate above design parameter.(2) Therefore, it is important to assess the possibility utilizing lower cost Material of Construction (MoC) in trajectory to short design life.
No prescriptive MoC specify in any international standard nor regulation in Indonesia, mentioning CRA shall be select at minimum first spool after production choke valve. It is part of corrosion study that shall be done to ensure appropriate material has been selected by oil and gas operator.

Several research has been done to identified damage mechanism associated with production hydrocarbon in sweet environment associate with sand or solid particle, where identified damage mechanism associate with this operation mode are combination of both CO2 corrosion and SEC.

The impact of CO2 corrosion has been deeply studied in several literature(3–6). As corrosive component (CO2, acetic acid, formic acid) dissolved in formation water contacts with bare steel pipe, uniform CO2 corrosion will take place, and causing the formation of corrosion product. And depend to formation water chemistry composition (Cl-, SO4-, Na+, Ca+, Mg+), Fe2O3 or FeCO3 layer expected to present at surface of bare steel pipe. CO2 dissolves into the boundary layer before it hydrates to form carbonic acid (H2CO3). In the boundary layer, H2CO3 dissociates to form hydrogen ion (H+), bicarbonate ion and carbonate ion. They all diffuse in the boundary layer. Carbonate ions may combine with the corrosion product, ferrous ions, to form FeCO3 which may eventually saturate the boundary layer and precipitate at the steel surface.(5) While Erosion-Corrosion mechanism has been address with interesting level of depth. (7–13)

Although literature above relevant with the expected damage mechanism, the focus of the study only on understanding the risk. There is no study focus consolidating all identified risk and bring the risks into design or moreover as recommended MoC, where selection of carbon steel pipe material might be limited the capability of pipe fabricator in providing required wall thickness as both corrosion allowance and hold up design pressure, thus attesting the important of creating more holistic methodology. In this sense, focus of this study is to take this identified damage mechanism and consolidate it into more structured and robust risk assessment, to define the mitigation and barrier required in utilizing the carbon steel pipe as production line. To help identifying the consequence, Event Tree Analysis (ETA) is being utilized. ETA is an inductive technique that have powerful function in identifying possible outcome of an accidental event. As it applied in design phase, it can provide proper barrier in achieving the design life.

The greatest contribution of this study is provision of proper guideline on how to quantify the risk, and setting the mitigation and barrier required in relevant with the reducing the expenditure cost.

Theoretical Background

In sweet environment, the corrosion likelihood of a carbon steel material, will be dependent on the concentration of dissolve CO_2 in electrolyte (water phase). It involves the formation of iron (Fe) ion in the anodic side and hydrogen (H_2) evolution at the cathodic side:(14)

Reaction in the water due to present of CO_2:

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad \text{(pH decrease)}$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

$$H_2CO_3^- \rightarrow H^+ + CO_3^{2-}$$

Where the anodic reaction:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$Fe^{2+} + CO_3^{2-} \rightarrow FeCO_3$$

Cathodic reaction:

$$H^+ + 2e^- \rightarrow H_2$$

$$H_2CO_3 + 2e^- \rightarrow H_2 + HCO_3^-$$

$$HCO_3^- + 2e^- \rightarrow H_2 + CO_3^{2-}$$

As shown on the reaction above, the present of CO_2 in the water, force the formation of carbonic acid (H_2CO_3), and lowering the environment pH. As consequence, causing aggressive attack on the carbon steel material(14). The final pH itself will depend on temperature and partial CO_2 pressure, where some study reveals that the environment pH with the presence of CO_2 will be above 4. While for the cathodic reaction, the presence of dissolve CO_2 increase the rate of hydrogen evolution. In pH > 4 solution, the presence of H_2CO_3 causing hydrogen evolution at much higher rate, which lead to much higher corrosion rate compare to in strong acid environment(15). Reduction of operation temperature and pH will produce thicker and more porous $FeCO_3$ layer. Thicker and porous FeCO3 layer also expected during jet flow occurred. As consequence of porous layer, diffusion rate of cathodic reactant allow to present, thus preventing the layer to act as protective layer.(16)

To predict the environment corrosiveness due to presence of CO_2, many modelling has been developed and utilized in industries, based on mechanistic approach (full theoretical), semi-empirical (partly theoretical), and empirical model (based on experimental). One of the most widely use mechanistic model is the de Waard and Milliams model, where the corrosion rate define as exponential factor of partial pressure CO_2 (pCO_2) and temperature(17)

$$log(R_{max}) = 5.8 - \frac{1710}{T} + 0.67\,log(pCO2) \quad (1)$$

Where R_{max} is the corrosion rate (mm/yr), T is liquid temperature (Kelvin), and pCO_2 is partial pressure CO_2

To improve the effect of pressure, especially for high operating pressure (pCO2 > 2 bar), it is important to switch from pCO2 to fugacity (fCO2)(18)

$$fCO_2 = a \times pCO_2 \qquad (2)$$

Where *a* is the activity coefficient:

$$log(a) = \left(0.0031 - \frac{1.4}{T}\right)P \qquad (3)$$

In attaining more realistic results, except pressure and temperature, it is important to consider the effect of (i)formation of protective film, (ii)presence of hydrocarbon due to oil-wetting to internal pipe, (iii)condensation and glycol, (iv)velocity, where it effect the transport of corrosives species and responsible to the removal of protective film, (v)corrosion inhibitor, increase the resistance to liquid erosion corrosion.(15,17,18) Hence, original model of de Waard and Milliams has been continually updated to extend its validity to actual operation condition, which has been deeply reviewed in previous study.(15) One of upgraded model, proposed by Nesic, by integrating the CO_2 corrosion prediction in the effect of multiphase flow regime, water layer thickness, velocity, wall shear stress, slug frequency, and water wetting/entrainment.(19)

Semi-empirical models are developed to simulate the corrosion behaviour of bare steel in water-CO2 system. One of semi-empirical model proposed by de Waard and Lotz by considering the experimental work of Wick and Fraser, where oil-wetting assume to occur once water cut less than 30% and liquid velocities higher than 1 m/s (all water expect to entrain in the oil phase). In 2001 and 2003, de Waard et al. continue to update the model by proposing new empirical correction factor for water wetting.

Empirical model most frequently utilize is the Dugstad et al model,(20) which has the same experimental database as de Waard model.(21) Develop based on the mechanical formulation of de Waard and collaborators, with some correction factor to temperature dependant, pCO2, pH, velocity (shear stress) and steel Cr content. This model has been utilize as NORSOK model and freely available.(19)

As initially discuss, the present of solid particle in the production fluid will affect in reduction of metal loss within two (2) forms. First form is direct thinning of the metal wall, and the second is through removal of the formation of corrosion layer $FeCO_3$. Where the second form is related to erosion-enhanced corrosion mechanism. Erosion-enhanced define as removal of corrosion product and/or protective film as consequence of sand presence, which enabling the corrosion process to continue occurred. Injection of corrosion inhibitor under this condition also will not give any beneficial since the protective layer will mechanically remove by the flowing sand. Hence, Erosion-Corrosion rate is defined as:

$$ECR = ER + CR + \Delta E_C + \Delta C_E \qquad (4)$$

ECR is the expected total erosion-corrosion thinning rate, ER is the independent erosion rate, CR is the independent corrosion rate, ΔEC is the effect of erosion-enhanced on the corrosion rate, and ΔCE is the effect of corrosion-enhanced on the erosion rate(7). Thus, the Erosion-Corrosion rate is not equal with the sum of independent erosion and corrosion rate.(22)

Corrosion-enhanced define as corrosion of work harden layer, exposing the underlying softer material. The work harden layer itself occurred due to solid particle impact on the metal surface resulting strain hardening of the material.(23) Some study has been done to quantify the exact effect of the erosion-enhanced corrosion and the corrosion-enhanced erosion, nevertheless as short as author literature review, the contribution of each on the total erosion-corrosion rate is still inadequate.(6–8,22,24–28) Refer to refs, corrosion-enhanced erosion is prominent at low particle velocity, whilst at higher particle velocity erosion-enhanced corrosion will be more prominent.(25) Latest study reveal the impact of corrosion-enhanced corrosion contribute in 20% increased of erosion-corrosion rate.(13) Thus, ECR can be simplified to:

$$ECR = (ER + CR + \Delta E_C) \times 1.2 \qquad (5)$$

Erosion-Corrosion effected by sand rate,(29) particle size,(30) impact angle,(31) pipe material hardness, surface roughness,(32) and fluid velocity.(26,27) More complex erosion wear can be attributed by present of several variables.(33) Since sands cannot be directly eliminated from SZ fluid production; some practice such sand cleaning using hydrocyclone, desander, or sand filter will increase capital and operational expenditure, thus decrease the financial profitability index. It is important to set limit on maximum sand produce, mitigation program, and monitoring plan.

ASSESSMENT METHOD

The proposed framework in quantifying the risk is comprised into five (5) stages and three (3) subcategories, which summarized in **FIGURE 1**. (i) determination of lifetime; (ii) determination of impacted section; (iii) erosion-corrosion assessment; (iv) determination of minimum CA required; (v) semi quantitative risk assessment; (vi) determination of consequence; (vii) determination of preventive and mitigation barrier.

Stage (i) define the required the design or operation lifetime of the production line. This data is important since it will be the basis to define the expected total metal loss. Once lifetime determine, the next important stage (ii) is to identify the cause of failure and followed by determination of impacted section. In relevant with this study, erosion-corrosion are defined as the most contributor failure causes. Hence the next stage (iii) is to quantify the probability of failure due to this damage mechanism. Erosion corrosion assessment consist of individual corrosion assessment, erosion assessment, and erosion-enhanced corrosion assessment. Corrosion-enhanced erosion is not considered in the assessment since literature mention it contribute to 20% of the erosion-corrosion rate, author consider as additional margin on calculated erosion-corrosion rate assessment, and the minimum corrosion allowance (CA) required in stage (iv). Once likelihood quantify, the next stage it to perform the stage (v) semi-quantitative risk assessment and followed by determination of consequence, in stage (vi), to define series of mitigation barrier required.

Several method has been established to quantify and assess the erosion-corrosion risk of carbon steel by performing experimental studies to obtain empirical formulae,(22,28,32)utilizing CFD (Computational Fluid Dynamic) modelling to predict the erosion rate from various flow pattern(29,30) or using semi-empirical model.(6) Furthermore, DNV also issued a recommended practice to manage the erosion under present of sand production(34). Each stage of assessment is performed as per below detailed:

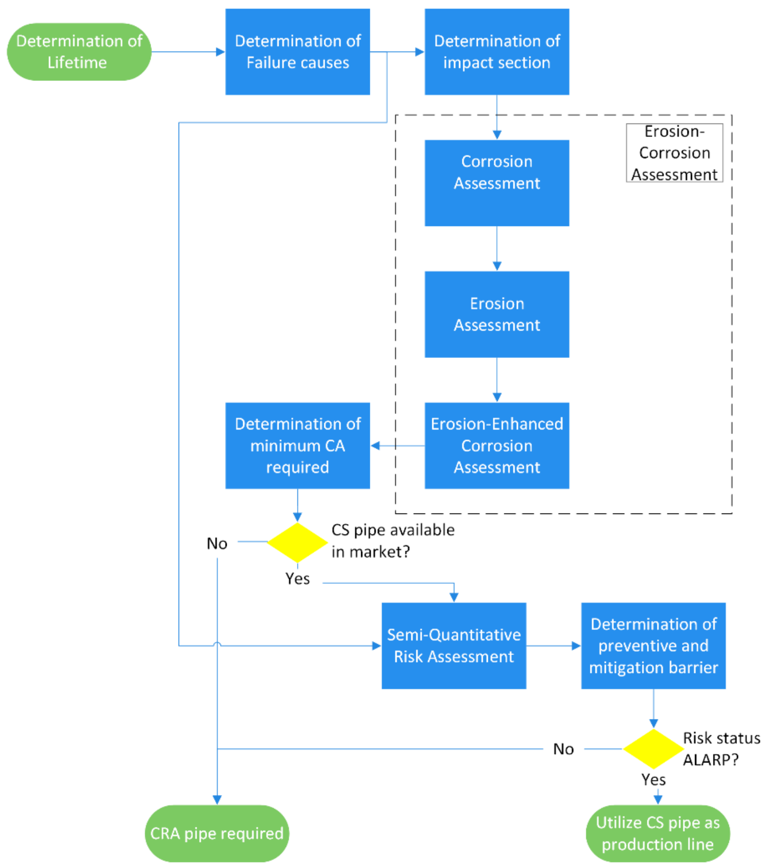


FIGURE 1. Carbon steel production flowline corrosion risk management framework

Corrosion Assessment

Assessment done by utilizing 3 (three) available software namely Corplus (software product of TOTAL), ECE (software product of Intetech), and NORSOK as stipulated in **TABLE 1.** NORSOK and CORPLUS are both empirical models. NORSOK were developed based on laboratory experimental data, while CORPLUS were develop based on TOTAL experience since early 80s. CORPLUS model contain complete pH/solubility calculation. Erosion – Corrosion evaluation are done with respect to liquid fluid without consideration of solid particle. Erosion – Corrosion is done with reference to API-RP 14E. Prediction of fluid corrosiveness are categorized to 5 (five) level: (i) very low

(< 0.1 mm/yr), (ii) low corrosiveness (0.1 – 0.3 mm/yr), (iii) medium (0.3 – 1 mm/yr), (iv) high (1 – 3 mm/yr), and (v) very high (3 – 5 mm/yr). While ECE is a semi-empirical model to predict corrosion rate of material in the presence of CO_2 and/or H_2S. The ECE model also include the pH calculation and the influence of oil wetting, the prediction of flow regime, and risk of Erosion – Corrosion as per API-RP 14E. (35)

TABLE 1. CO_2 corrosion assessment model comparison(35)

Parameter		CORPLUS	ECE	NORSOK
Lab data (L), Field Data (F), Mech. Model (M)	:	F	L	L
Scale effect (formation water)	:	W	W	M
Scale effect (condensed water)	:	W	W	M
pH on Corrosion Rate	:	M	W	M
Risk Localized attack	:	Y	-	-
Oil wetting	:	M	S	N
Condensate wetting	:	M	M	N
CaCO3 Correction in pH	:	Y	-	-
Organic acid	:	Y	Y	-
H_2S effect	:	N	Y	N
Multiphase flow calculation	:	P	P	Pr

Note: N - No effect, W - Weak, M - Moderate, S - Strong effect, P - Point calculation, Pr - Profile calculation, Y - Yes, - not consider

Erosion Method

Erosion are assessed base on guideline provided in DNVGL-RP-0501 2018 version (34) and by utilizing the model developed by university of Tulsa within E/CRC program namely SPPS: E-C. Refer to piping configuration, 3 case are being selected to represent the overall pipe configuration, those are straight line, elbow, and direct impingement (or blind tee).

DNVGL-RP-0501 are solid particle erosion empirical model developed driven by quartz sand as an erosive agent, with minimum particle size of 20 micron (μm).

Particle impact velocity considered similar with mixed fluid velocity. Expected metal loss due to solid particle impact is proportional to sand rate exposed to internal pipe surface. The guideline only applicable to assess pure erosional impact, and not compatible to assess the risk of Liquid Erosion Corrosion (LEC), droplet erosion, or cavitation.

$$ER_{straight} = 2.5 \times 10^{-5} \times U_p^{2.6} \times D^{-2} \times m_p \qquad (6)$$

$ER_{straight}$ is erosion rate at straight line in mm/yr, U_p is the particle impact velocity in m/s, D is the inner pipe diameter in metre, and m_p is the sand rate in kg/s.

$$ER_{elbow} = \frac{K \times F(\alpha) \times U_p^n}{\rho_t \times A_t} \times G \times C_1 \times GF \times m_p \qquad (7)$$

ER_{elbow} is erosion rate at elbow section in mm/yr, K and n is material coefficient driven based on combination of material type and its erosive agent, F(α) is characteristic function of ductile material, U_p^n is the particle impact velocity in m/s, ρ_t is the pipe material density, G is the solid particle correction factor, $C_1$is model factor, and GF is geometry factor.

$$ER_{blind} = \frac{m_p \times K \times U_p^n}{\rho_t \times A_t} \times G \times C_1 \times GF \times m_p \qquad (8)$$

ER_{blind} is erosion rate at blind tee or direct impingement cases section in mm/yr,

The second modelling use is SPPS: E-C. SPPS: E-C is an erosion programming model. It calculated the expected erosion rate (ER) as effect of sand present by considering the sand density, particle rate, particle size, fluid density, flowrate, flow geometry, and material properties. The ER is formulated in: (16)

$$ER = F_M \times F_S \times F_P \times F_{r/D} \times \frac{W \times V_L^{1.73}}{D^2} \qquad (9)$$

ER is erosion rate at elbow in mm/yr, F_M is correction factor for material hardness, F_S is sand sharpness factor, $F_P$is penetration factor for steel, $Fr_{/D}$ is penetration factor at elbow radius, W is the sand rate in kg/s, VL is particle impact velocity in m/s, and D is ratio pipe diameter to a 1-inch pipe. In term of uniform metal loss upon metal surface area, ER is calculated as: (36)

$$ER = \frac{A \times F_S \times V_L^{1.73} \times F(\theta) \times W}{\rho_{wall} \times A_{wall}} \tag{10}$$

A is wall dependent as function of material hardness, ρ_{wall} is material density, A_{wall} is material surface area.

Semi-Quantitative Risk Assessment (SQRA)

SQRA method is invented in 2007 as an improvement of qualitative method.(37) It is a risk evaluation of potential failure modes based on its likelihood and consequence, also known as “risk matrices”. SQRA is the important stage to be done in design phase, as risk can be identified and quantified properly, and risk control can be applied to reduce the risk level. SQRA might be applied by combination of qualitative technique with measurement or modelling to quantify the consequence and likelihood of a failure mode.(38) Objective of the method is to plot each identified risk in the matrix according to the probability of the event to occur and the severity once the event has occurred.

Once the initial risk has been plotted, it is important to define area of acceptance. If the risk is not accepted, then set of barriers shall be establish as control measure to reduce the risk to As Low As Reasonably Practicable (ALARP). Failure mode scenario are assessed according 5 (five) categories: (i)asset (ii)production (iii)environment (iv)human (v)media. Detail classification of 6x6 matrices is recommended, with detail as shown in **FIGURE 2**. Classification of likelihood shown in **TABLE 2**, while risk consequences are shown in **TABLE 3.**

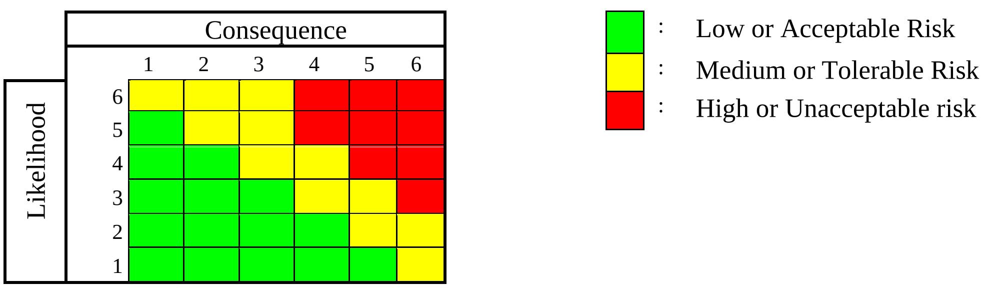


FIGURE 2. Semi Quantitative 6x6 Risk Matrices

TABLE 2. 6x6 risk matrices likelihood classification (40)

Likelihood		Describe definition
Remote, < 10^{-5}	:	Event physically possible but has never or seldom occurred over a period of 20 to 30 years for a large number of sites
Extremely Unlikely, 10^{-} – 10^{-5}	:	Has already occurred in the INDUSTRY but corrective action has been taken
Very Unlikely, 10^{-3} – 10	:	Has already occurred in the COMPANY but corrective action has been taken
Unlikely, 10^{-2} – 10^{-3}	:	Could occur once for every 10 to 20 similar plants over 20 to 30 years of plant lifetime
Likely, 10^{-1} – 10^{-2}	:	Could occur several times during over plant lifetime
Very Likely, < 10^{-1}	:	Expected to occur several times during plant lifetime

TABLE 3. 6x6 risk matrices severity of consequence (40)

	Production Shortfall	**Media**	**Material**	**Environment**	**Human**
Minor	<2K BOE	Local rumor or no media consequence	<20K €	Minor spill with no environmental impact	First aid or medical treatment or restricted workdays
Moderate	>2K, <20K BOE	Local rumor / regional press	20K - 200K €	Minor pollution with a very limited environmental impact	Single lost-time injury (LTI) with no disability
Serious	>20K, <200K BOE	Regional press + regional TV, national rumor	200K - 2M €	Moderate pollution with limited environmental consequences	Single lost-time injury (LTI) with disability or multiple lost-time injuries
Very Serious	>200K, <1M BOE	National press + national TV	2M - 10M €	Pollution having significant environmental consequences	Internal: 1 Fatality and/or several disabilities Public: Disabilities
Catastrophic	>1M, <10M BOE	International press + international TV	10M - 100M €	Large-scale pollution of ecosystems having a recognized ecological value	Internal: 2 to 5 Fatalities Public: 1 Fatality
Disastrous	>10M BOE	International press + international TV for prolonged period	>100M €	Pollution having massive and durable consequences for vast ecosystems having a high ecological value	Internal: >5 Fatalities Public: >1 Fatality

No immediate action required if identified risk drop at green – acceptable area. For risk drop at Medium or tolerable area, a risk control measure is recommended to be assessed to ensure the residual risk considered as ALARP. While each risk drops at high or unacceptable area, a risk control measure shall be done to substantially reduce to medium or low level.

CASE STUDY

This section presenting the real case study done for one of oil and gas in Indonesia, which perform in accordance with the proposed framework in offshore production facilities. Upon realization of real case, it does not allow complete evaluation of proposed framework effectiveness, since the submitted cases currently still in Engineering-Procurement-Construction-Installation stage (PCI), thus actual thinning rate cannot be verified.

Design Parameter

Following practice by proposed company, no further study to be done on Material of Construction in EPCI stage (limited engineering), thus the design parameter is taken from Front-End Engineering Design (FEED) stage as shown in **TABLE 4**.

TABLE 4. Real case design parameter

Parameter	Value
Design lifetime	5 years
Production Capacity	15 MMSCFD maximum well capacity
Liquid Flowrate	CGR 26 bbl/MMscf WGR 10 bbl/MMscf
Sand production rate	0.02 g/s (MASR), with Gravel Pack installation
Max Operating Temperature	75 degC
Max Operating Pressure	35 bara

Maximum Allowable Sand Rate (MASR) is set as allowable sand rate refer to permanent Acoustic Sand Detector (ASD) measurement, which connected to production alarm system. Reservoir water chemical composition are stipulated in **TABLE 5**. No dissolved gas concentration measurement done, thus below data summarized in **TABLE 6**. are taken from the gas composition, as state in company design basis.

TABLE 5. Corrosives gas composition

Gas Composition	Value
CO_2	2.73 %
H_2S	0 %
O_2	< 20 ppb

TABLE 6. Reservoir water chemical composition

Ion	Value (mg/L)
Chloride (Cl^-)	13724.3
Bicarbonate (HCO_3^-)	3574.6
Carbonate (CO_3^{2-})	0
Sulphate (SO_4^{2-})	0
Acetic Acid	150
Sodium (Na^+)	9775.1
Potassium (K^+)	270.4
Calcium (Ca^{2+})	240.5
Magnesium (Mg^{2+})	69.1
Total Iron (Fe^{2+})	2.7
Barium (Ba^{2+})	5

Corrosion Study

Corrosion study perform shows, empirical models predict max 0.8 mm/yr corrosion rate, while the semi-empirical model predicting more than 3 mm/yr.

TABLE 7. Corrosion simulation result comparison

Parameter	*CORPLUS*	*ECE 5.6*	*NORSOK M-506*
CO2 Corrosiveness	Very Low (<0.1 mm/yr)	-	-
Partial CO2 (bara)	0.815	0.81	-
Potential Corrosivity (mm/yr)	1.91	3.27	0.8
Natural pH	6.46	7.13	6.4 (assume)
Acetic Acid (Meq)	0.05	-	-
Saturated FeCO3	32.76	-	-
Saturated CaCO3	62.99	-	-

CaCO3 precipitation quantity (mg/l)	586.17	-	-

CORPLUS Simulation

Simulation done using CORPLUS version 3.0, where it has been upgraded to consider oil-water wetting criteria. Since CORPLUS is empirical model, it only suit to be utilized under area of application as shown in **TABLE 8**

TABLE 8. CORPLUS area of application

Criteria	pH Evaluation	Corr. Evaluation
Temperature (degC)	5 – 150	5 – 150
pH	3 – 7	3 – 7
pCO2 (bara)	0.01 – 50	0.01 – 20
Ionic Strength (M/L)	0 – 5	0 – 5

Under conditions of no protective layer formation, the expected corrosiveness is represented by two values (i)Potential Corrosivity (PC) value, where define as quantitative uniform corrosion rate of bare steel in contact with produced water. (ii)CO_2 corrosiveness, where define as the qualitative actual capacity of the produced water to corrode the steel surface at given calculation conditions. As define in the manual, any expected corrosiveness is taken by comparing these 2 (two) values. Any value with lowest prediction shall be utilized as expected fluid corrosiveness. Results in **TABLE 7**, shows “Very Low” CO_2 corrosiveness and PC of 1.91 mm/yr, thus the expected Corrosiveness is 0.1 mm/yr.

PC prediction shows significant ordo of magnitude if compared to qualitative CO2 corrosiveness. This occurred by assuming carbon steel pipe continuously water wetted and come from the initial corrosion rate of bare steel once it in contact or immersed with its electrolyte. This makes the PC prediction as more conservative assumptions, to show the worst corrosion rate might occurred under circumstances.

ECE Simulation

Simulation done using ECE version 5.6 with results as shown in **TABLE 7**. Results at 75 degC and 35 bara, predicted a 6” carbon steel pipe will experience around 3.27 mm/yr, hence for 5 years design life, minimum corrosion allowance (CA) required will be 16.5 mm. Very high corrosion rate is predicted by the ECE model, as mentioned in the ECE manual, this occurred to ECE taken the maximum corrosion rate it might occurred as its predicted corrosion rate. There is no sign of protective FeCO3 layer effect, under this assessment condition, as corrosion rate continue increased by the increasing of operating temperatures.

TABLE 9. ECE Corrosion Simulation Results

Parameter	***41 degC***	***75 degC***
CO2 Corrosion rate (mm/yr)	1.94	3.27
Pitting risk	-	-
CO2 Partial Pressure (bar)	0.81	0.81
pH	6.86	7.13

NOSROK Simulation

Simulation done using NORSOK M-506 version 2. The model only able to be utilized under area of application shown in **TABLE 10**. Results shown in **FIGURE 3**, where it shows the expected corrosiveness is 0.8 mm/yr. Higher corrosion rate is expected once the environment pH drop to 6.3, with prediction of 1.1 mm/yr.

TABLE 10. NORSOK M-506 area of application

Criteria	Value
Temperature (degC)	5 – 150
pH	3.5 – 6.5
pCO2 (bara)	0.1 – 10
Shear Stress (Pa)	1 – 150

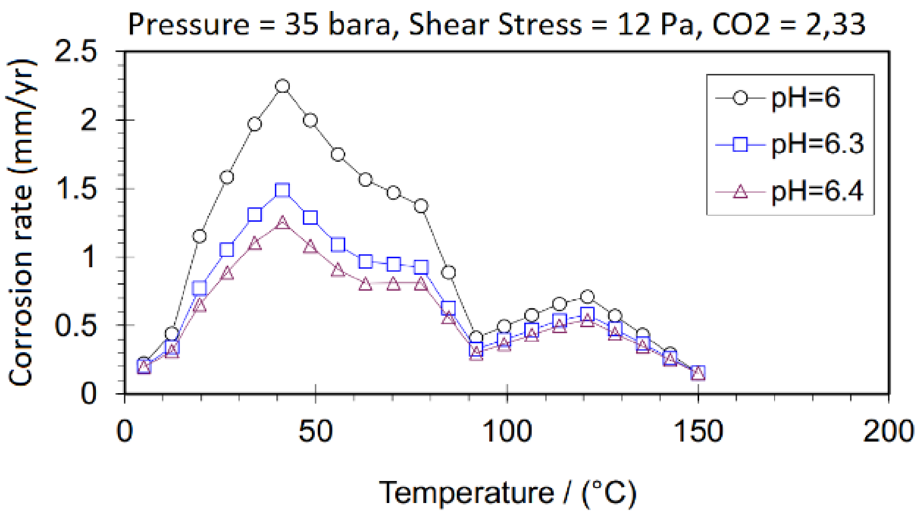


FIGURE 3. NORSOK M-506 CO2 corrosion prediction under different environment pH

Unfortunately, since predicted pH is more than 6.5, while the model only valid for maximum pH 6.5, therefore value generate for pH 6.4 are taken as representation. This approach considered valid, since expected corrosion rate reduced by pH increasement. pH 6.4 is use as it is the lowest pH value predicted

Erosion Study

Erosion studies results utilizing DNVGL-RP-0501 and SPPS: E-C shows a maximum of 1.6 mm Metal loss is expected within 5 years design life, which trigger by direct impingement case. Depend on the piping configuration, direct impingement case is expected to occur at production choke and blind tee piping system.

DNVGL-RP-0501 Simulation

Erosion simulation results as per DNVGL guidelines prediction shows a 6" carbon steel pipe will experience a minimum 1.3E-06 millimetre metal loss is expected for straight line, 3.61E-02 millimetre metal loss at elbow pipe, and 1.11E-01 millimetre is expected due to direct impingement. Particle impact velocity as per DNVGL-RP-0501 is equal to fluid mixture velocity. Thus, its movement and energy consider similar with fluid movements.

For elbow and direct impingement cases, higher erosion rate is predicted compared to straight due to particle impact angle, ratio particle to mixture density, particle size, and pipe geometry. While for straight cases, it is only affected by the particle impact velocity due to particle along with the mixture flow.

SPPS: E-C Simulation

Erosion simulation results as per SPPS: E-C model prediction shows a 6” carbon steel pipe will experience a minimum 2.85E-03 millimetre metal loss is expected for straight line, 0.80 millimetre metal loss at elbow pipe, and 1.60 millimetre is expected due to direct impingement.

SPPS: E-C modelling shows particle moves in higher velocity compared to its fluid velocity. This means, the particle movement is not inline with fluid movement and accelerate by another parameter. The higher erosion rate prediction of SPPS: E-C are contributed due to difference in prediction of particle movement. **TABLE 11** shows particle impact velocity increased as function of particle impact angle.

TABLE 11. Solid erosion simulation results using DNVGL-RP-0501 and SPPS: E-C

Parameter	DNVGL-RP-0501	SPPS: E-C
Superficial gas velocity (m/s)	16.54	12.97
Superficial liquid velocity (m/s)	0.075	0.082
Particle Impact velocity (m/s)	16.616	27.53 (straight case) 33.12 (elbow case) 39.92 (direct impingement case)
Viscosity fluid mixture (kg/m.s)	1.46E-05	1.7E-05
Straight Pipe Metal loss (mm/yr)	2.6E-07	5.7E-04
Elbow pipe Metal loss (mm/yr)	7.22E-03	0.16
Direct impingement/Blind tee (mm/yr)	2.21E-02	0.32

Erosion-Enhanced Corrosion

Erosion-enhanced corrosion are predicted in accordance with API-RP-14E and studied in basis of protective layer removal due to abrasion by fluid movement.

For design case, where solid and/or corrosive contaminant are expected, calculation of fluid erosional velocity (V_{API}) shall be studied using appropriate “C factor” using industrial experience. Total E&P and Pertamina Hulu Mahakam experience, in condition where no inhibition is expected to perform recommended “C factor” is 100 $lbs^{0.5}.ft^{0.5}.s^{-1}$, which calculated as follow

$$V_{API} = \frac{C_{factor}}{\sqrt{\rho_m}} \tag{11}$$

Mixture density (ρ_m) calculated as per following equation:

$$\rho_m = \frac{Q_{oil}+Q_w+Q_g}{\left(\frac{Q_{oil}}{\rho_{oil}}\right)+\left(\frac{Q_w}{\rho_w}\right)+\left(\frac{Q_g}{\rho_g}\right)} \tag{12}$$

Fluid flowrate (Q_{oil}, Q_{water}, Q_{gas}) present in kg/hr, while fluid density in kg/m^3.

Erosion-enhanced corrosion is expected if the mixture velocity is higher than V_{API}, where in this case calculated V_{API} is 17.64 m/s. Comparing both mixture velocity calculated by both DNVGL-RP-0501 or SPPS: E-C to V_{API}, it is concluded that, possibility of erosion-enhanced corrosion is unlikely. Following approach state in equation 5, the total expected erosion-corrosion rate (ECR) is:

$$ECR = (0.32 + 0.8 + 0) \times 1.2 = 1.344\ mm/yr$$

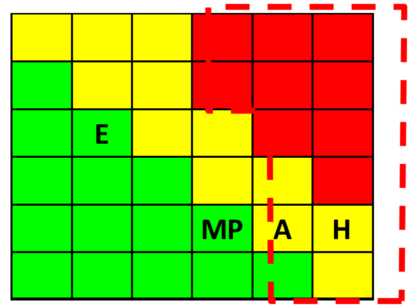
Hence, the total metal loss within 5-years design life is 6.72 mm.

SQRA Assessment Study

For appropriate SQRA results, it is important to perform the assessment involving at minimum Production Operation, HSSE, Inspection and Maintenance, Engineering, and Integrity subject matter expert. Initial risks are assessed for each category: human (H), environment (E), asset (A), media (M), Production (P). Results are shown in **FIGURE 4**

Evaluation	Initial Risk				
	H	E	A	M	P
Severity	6	2	5	4	4
Likelihood	2	4	2	2	2

(a) Initial risk detail value



(b) Initial risk matrices plotting

FIGURE 4. 6x6 Initial Risk Assessmen

Control measure to ALARP is recommended, especially for "high" risk and any risk with consequence level 5 and 6 (mark in dashed zone). **FIGURE 4** shows once failure occurred to the scenario of utilization of carbon steel pipe as 1st spool well production line, it will cause catastrophic (level 5) consequence to assets. And it will also cause a disastrous (level 6) consequence to human.

During the assessment done, all subject matter agrees, that no mitigation can be put to reduce the consequence, instead control measure to reduce likelihood are considered. As per shown in

TABLE 12,Inspection strategy is set as preventive barrier, as its proper application will act as early detection of failure. The assessment also recommends flange-to-flange connection for the 1st spool to ease the pipe replacement.

No	Mitigation Action	Action By	Target Date	Action Status	Remark
1	Sufficient Corrosion Allowance	ECP/PJT	DONE	Accepted	5 years' design life requires minimum CA 6.72 mm thick based on calculation. As per production figure, production life less than 5 years of production service, thus lower thinning rate is expected
2	Perform first in-service inspection after 1 year operation	FO	1st year in-service	Accepted	To inspect and evaluate the thinning rate at 1st spool pipe is less than 1.344 mmpy, refer to Technical Note calculation issued
3	Flange connection at first spool for easier spool replacement	ECP/PJT	EPCI stage	Accepted	To ease pipe replacement (in case of), reduce production shortfall

No	Remedial Action	Action By	Target Date	Action Status	Remark
1	Point type GD are installed closer to xmas tree	ECP/PJT	EPCI Stage	Accepted	To increase chance to detect gas leak from 1st spool

This reduces the risk consequence to production category (P) to "Serious" (level 3) as it aims to shorten the repair/replacement duration. Gas detector also recommend to installed closer to xmas tree to increase the chance of detection once failure occur. Final risk level target, after putting the control measure are shown in **FIGURE 5**

No	Mitigation Action	Action By	Target Date	Action Status	Remark

1	Sufficient Corrosion Allowance	ECP/PJT	DONE	Accepted	5 years' design life requires minimum CA 6.72 mm thick based on calculation. As per production figure, production life less than 5 years of production service, thus lower thinning rate is expected
2	Perform first in-service inspection after 1 year operation	FO	1st year in-service	Accepted	To inspect and evaluate the thinning rate at 1st spool pipe is less than 1.344 mmpy, refer to Technical Note calculation issued
3	Flange connection at first spool for easier spool replacement	ECP/PJT	EPCI stage	Accepted	To ease pipe replacement (in case of), reduce production shortfall

TABLE 12. Control measure recommendation as per Risk Evaluation Task (RET)

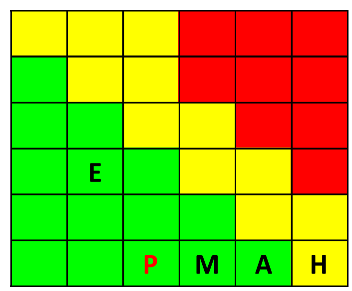
This arrangement considers satisfied, as inspection program at 1st year in-service also able to compensate, should actual corrosion rate (CR) increase as per ECE modelling. Nevertheless, inspection planning shall be clearly done and

No	Remedial Action	Action By	Target Date	Action Status	Remark
1	Point type GD are installed closer to xmas tree	ECP/PJT	EPCI Stage	Accepted	To increase chance to detect gas leak from 1st spool

followed, as no inspection backlog allowed.

Evaluation	Residual Risk				
	H	E	A	M	P
Severity	6	2	5	4	3
Likelihood	1	3	1	1	1

(a) Residual risk detail value



(b) Residual risk matrices plotting

FIGURE 5. 6x6 Target residual risk assessment

Event Tree Analysis (ETA)

SQRA performed above shows, further evaluation required to accept the consequence of utilization carbon steel pipe on human and asset. Hence ETA is recommended to applied. It defines the outcome once an event occurred.

To define the probability, several assumptions must be considered. The first, whether the release immediately ignite or if there is delayed. It is best to considered worst case severity, due to during end-of-life mode, any unplanned corrective action as consequence of failure, may not be feasible to be taken and will cause permanent loss of production. Hence in immediate ignition cases, for pressurized gas and multi-phase Jet Fire (JF) scenario is considered. While for delay ignition, the outcome of the event split into Flash Fire (FF) and Unconfined Vapour Cloud Explosion (UVCE) scenario. It is assumed that a flammable gas cloud ignition has 60% probability to generate FF and 40% to generate UVCE. The second, release gas is not ignited. In this case, toxic release, pollution, or unignited dispersion (non-hazardous) event is assumed. For report simplicity, ETA for delay ignition is not shown in this paper.

Detection system considered applicable are dedicated fire and gas (F&G) detector, low pressure switch (PSL), and manual operator detection. The probability of successful detection, isolation, and blowdown for each detection system are various. For F&G detector, the failure probability (PF) of detector taken equal as SIL-2 system 0.01. For PSL, in case rupture release PF is equal to SIL-1 system 0.1. While for small or medium release PF is consider 1 due to in multiphase flow, the small and medium release will not directly be causing pressure drop in the system.

For F&G detector, other factor important to consider is the probability of a release "reaching" a gas detector (PR_{GD}). Hence it is important to ensure proper distribution, by considering release size and wind/release direction. Assumption made for small release PR_{GD} is 0.5, for medium and rapture PR_{GD} is 0.9, while for an adequate distribution PR_{GD} is 1. Hence overall probability of successful of each detection (P_{DETECT}) system are formulated as follow:

<u>F&G detector</u>

$$P_{DETECT} = (1 - PF_{F\&G}) \times PR_{GD} \tag{13}$$

<u>PSL</u>

$$P_{DETECT} = (1 - PF) \tag{14}$$

As shown in **FIGURE 6** for immediate ignition and the effectiveness of process detection and successful of deluge system as combat system will give no negative consequences. Unfortunately, both barrier availability is very low, due to small and medium rapture will not directly affecting the system pressure drop to low pressure alarm level (PALL) and unmanned platform respectively. Hence, it is important to ensure the availability and reliability of F&G detector and the isolation system.

CONCLUSION

There is no doubt, as the reservoir depleted, each operator entities are challenged to reduce their operation expenditure. Hence, it is important to perform risk evaluation, to identify each associate risk and define the control measure required, to enable operate at tolerable risk (ALARP).

This paper has proposed a recommended framework in implementing risk management to the selection of Material of Construction (MoC). The important of the guideline are clearly highlighted by the real case study perform, showing how the risk shall be considered and quantified, and the importance of performing risk evaluation.

Results from the show case study shown under similar production parameters, the available corrosion prediction tools and erosion prediction tools shows different ordo of magnitude in predicting the fluid corrosiveness. Hence based on both results of damage prediction, the utilization of carbon steel is not feasible, due to more than 10 mm corrosion allowance required, which is outside pipe fabricator capability. Therefore, it is proposed to predict the consequences and set mitigation control to reduce the consequences to ALARP, by means of ETA.

The main objective of the framework is to highlight that, as none of corrosion prediction can accurate and precisely predict the corrosion phenomenon, a set of several evaluation task is required, to gain higher confidence level. And the task shall be carried out by competence and relevant team. It also important to set some room for uncertainty, hence some conservatism shall be carefully considered during performing the risk evaluation.

It is acknowledged that, there is still gap since the submitted cased has not been put in production, hence the actual condition cannot be verified. As consequence, the study has miss one variable input, which is operation feedback. Where it can reveal unidentified risk associated with the scenario evaluation. Therefore, it important once the complete framework has been done, the next important step is to perform re-evaluation of the implementation. Hence entity in charge shall be defined to monitor and maintain all the risk evaluation performed. In continuation of the development of this research, it is also important to predict the trend of thinning at this section. A risk based inspection approached, utilizing non-linear stochastic modelling should give advantages, as it can give confidence in setting inspection frequency(39)

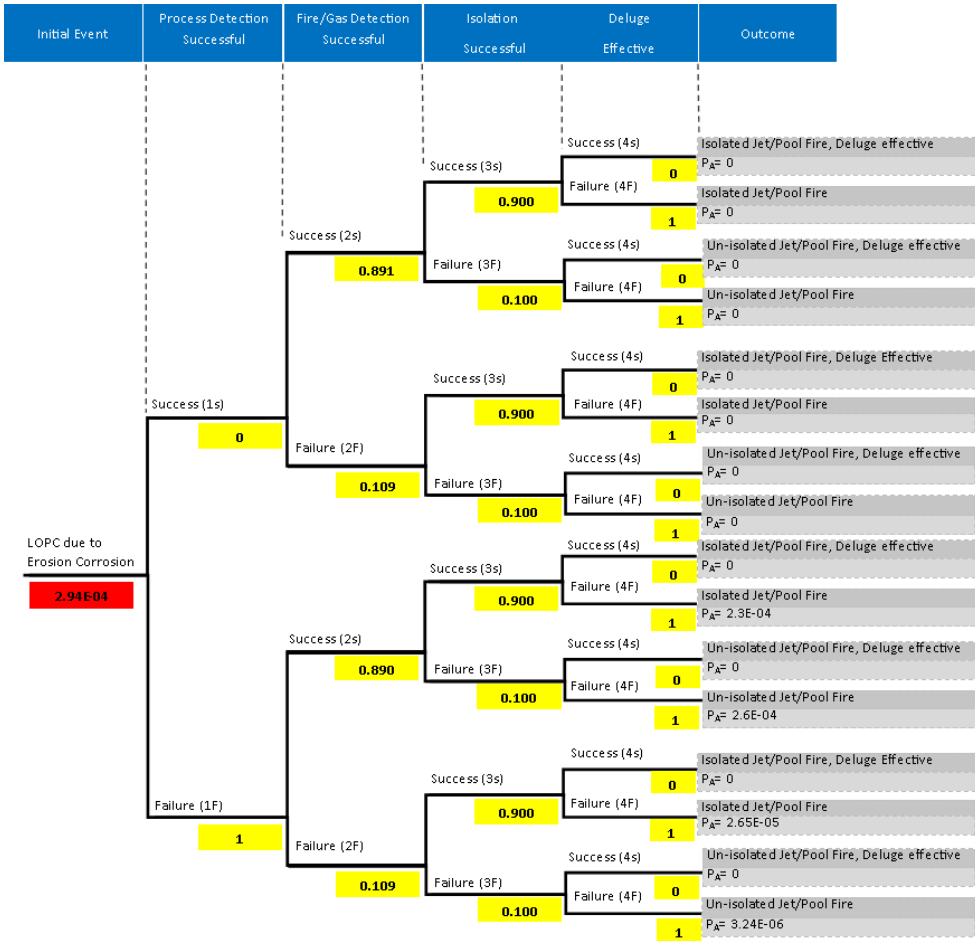


FIGURE 6. Event Tree Analysis of LOPC with immediate ignition

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